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ANALYSIS AND SYNTHESIS OF FUNCTIONAL COATINGS BY HIGH-SPEED LASER PROCESSING OF ULTRAFINE POWDER COMPOSITIONS

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ABSTRACT

The article analyzes the features of the destruction of functional coatings. The technology of obtaining functional coatings for various purposes by the method of high-speed laser synthesis of ultrafine powder materials with a gradient structure and mechanical properties is proposed. The results of laboratory and operational studies of functional coatings are presented. The research results demonstrate the excess of the physicomechanical properties of the analyzed coatings in comparison with similar and standard surfaces. The results obtained provide a visual representation of the prospects of high-speed laser synthesis technology of various functional coatings and have a high practical potential.

KEYWORDS: Analysis, High-Speed Laser Processing, Functional Coating, Wear Resistance, Powder Material, Antifriction Properties

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Original Article

INTRODUCTION

The current socio-economic situation in Russia and the level of industrial development are characterized by a reduction in the resource potential, the degradation of the material and technical base, and therefore questions have arisen to improve them (Gogaev(2018), Ostaev (2018) a, Ostaev (2018) b, Ostaev (2019)).

Modern engineering cannot be imagined without contacting surfaces in the nodes of machines and units. The resulting friction between the contacting surfaces is necessary to ensure the transfer of mechanical energy from one mechanism to another. In this case, the physico mechanical processes occurring in the contact zone adversely affect the wear resistance of surfaces and, in general, the durability of the assembly. Therefore, the task of increasing the resistance of the contacting surfaces to various types of effects (wear, thermal, fatigue, oxidizing, etc.) are the most relevant and require extensive research. The search for new solutions in the field of materials science, in particular, the creation of functional coatings on the contacting surfaces of machine parts is one of the areas of research. The creation of functional coatings for various purposes began to develop with the implementation of PVD - and CDV - technologies in the 70-80s of the 20th century. However, their implementation involves a number of drawbacks, which are associated with significant limitations on the substrate material, the "purity" of the process and the requirements for the filler material. The highest interest in mechanical engineering is caused by the technology of obtaining functional coatings using highly concentrated energy sources, in particular, laser radiation (Maeda (2004), Strelkov (2010), Goldfarb (2015), Ipatov (2018)). In this paper, we consider some functional coatings synthesized by high-speed laser treatment of ultrafine powder materials.

The operability of functional coatings and surfaces of machine parts and mechanisms depends on three

factors: 1) internal, determined by the properties of materials; 2) external, characterizing the type of friction, the speed of relative movement, load, temperature of the medium; 3) working environment. The initial period of interaction of the contacting surfaces, the destruction occurs mainly as a result of the intermeshing of surface irregularities. This leads to the formation of loose wear products that define abrasive wear of surfaces. Wear occurs with repeated deformations, which lead to physical or chemical changes in the surface layer and accumulation of damage in it, leading to the separation of individual particles. Regardless of the materials of the interacting surfaces, the dynamics of destruction can be represented in the idea of the main processes: 1. The destruction of the material along the grain boundaries as the weakest points of the metal conglomerates. 2. The mechanics of destruction corresponds to the basic laws of the distribution of forces in solids. In accordance with the above, the scheme of action of forces applied to a metal surface, based on grains of metals, can be represented as follows (Figure 1).

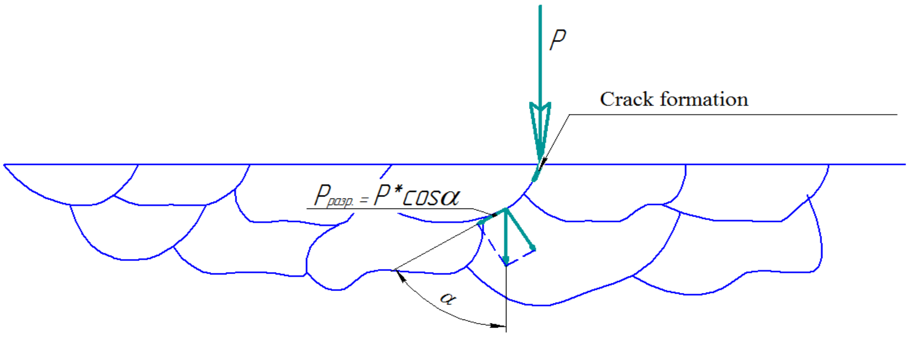


Figure 1: Diagram of the Distribution of Destructive Loads at the Grain Boundaries

A load applied to one of the surfaces, the magnitude of which is determined by the force characteristics of the mechanism, has a destructive effect on the grain boundaries. When the direction of the load coincides with the grain boundary, the repeated action of forces changes the mechanism of intergranular interactions: a) the bonds between the grains are destroyed; b) impurity inclusions in alloys located between the grains move between them to the most favorable zones, aided by oscillations of adjacent grains, which carry the released impurity inclusions from the interaction zone, forming a microcavity called a microcrack. The intensity of intergranular damage is determined by the magnitude of the load on the interface. However, with an increase in microcracks, the destructive force, which is always a component of the applied load, decreases, whereby the intensity of destruction also decreases, which follows from the destruction scheme. It should be noted that due to the natural laws of the grain during the formation always tend to a spherical shape, to the form with a minimum amount of energy. Because of this, the destructive force becomes minimal when approaching the lowest point on the surface of the grain. The final separation of the grain from the surface of the part is caused by constantly acting compressive and tensile deformations.

On the basis of the above, the resistance of surfaces to destruction is largely determined by the dispersion of the grains. In the case of a fine-grained structure, the loss of a unit of dimensions of the surface will require more forceful deformations on the destruction along the boundaries, since the area of destruction will be larger than that of the coarse-grain. Therefore, the task of obtaining functional coatings is reduced primarily to obtain a fine structure, which can be implemented in conditions of high rates of super cooling of the filler material. However, high super cooling rates in the synthesis of thin functional coatings are undesirable because they cause intense internal stresses, leading to cracking and peeling of the coating from the substrate. Therefore, to solve this problem, many developers resort to multi-layer coating technologies (Kharanzhevskiy (2015), Goldfarb (2015)), which are implemented step by step with the application of

several layers of different chemical composition and structure (Figure 2).

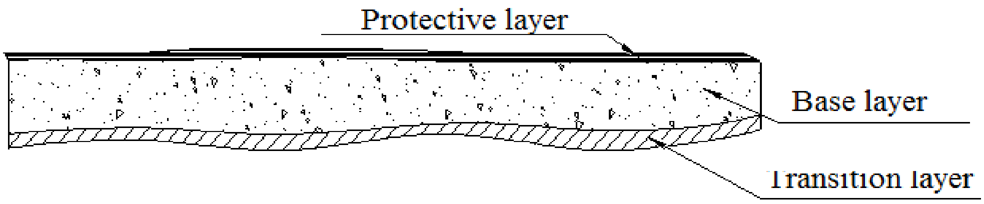


Figure 2: The Structure of the Majority of Multilayer Coatings

As a rule, multilayer coatings are characterized by a transition layer, which serves as a barrier and prevents diffusion of the components of the main coating deep into the substrate. In this case, the transition layer in its physical properties may differ significantly from the structure of the main coating, as well as the substrate. The transition layer does not experience dynamic loads, so its mechanical properties are not controlled, the main task of this layer is to provide increased adhesion of the base layer to the substrate surface, and it serves as a thermal barrier in some cases (heat resistant coatings of turbine blades). The base layer of multilayer coatings carries the main dynamic load, therefore it is synthesized from solid and durable materials, mainly powder compositions using various technologies. The auxiliary or protective layer serves to prevent oxidation of the base layer, reduces the risk of unwanted mechanical damage, in some anti-friction coatings serves as a running-in layer. Despite the success and availability of multilayer coatings, many manufacturers in the engineering industry negatively respond to this technology, because these coatings are characterized by low fatigue strength, which leads to delamination of the coating from the base, high cost of products, as well as limited functionality. The most promising type of functional coatings is a single-layer gradient structure, which is implemented in one pass from a single filler material. The mechanical properties of gradient functional coatings vary in thickness and have higher versatility. The gradient of thickness properties is realized due to a change in the structural and phase composition of the coating. Phase change is largely implemented by the features of the structure formation of the coating under conditions of high temperature gradients and cooling rates. The most favorable conditions for obtaining such coatings are realized with high-speed laser processing, which allows for a high temperature gradient at the interface with a high kinetics of mass movement during fusion with the formation of unique structures (Kharanzhevskiy (2015), Haranzhevskiy (2004)). However, the implementation of the technology of obtaining functional coatings using high-speed laser radiation is impossible without the presence of an optimal filler material. The most optimal material is a powder medium with the introduction of additional components to increase the efficiency of absorption of laser radiation. At the same time, the dispersion of the powder material also plays an important role, the use of highly dispersed powder materials is more preferable. The main advantage of using a highly dispersed powder medium is the high density of the structure being formed, as well as a high proportion of the emitted liquid phase. Obtaining coatings from powder materials can be carried out using traditional powder metallurgy processes with an insignificant amount of liquid phase (up to 5%), which is typical of low-capacity sintering and sintering processes. Under the conditions of high-speed processing, it was proved (Haranzhevskiy (2004), Ipatov (2018), Ipatov (2015)) that the optimal formation of a coating is possible with a liquid phase in the range of 40-45% by weight of the mass of the powder composition. Therefore, in this paper, we consider the formation of functional coatings by the method of high-speed laser treatment of ultrafine powder materials.

METHODOLOGY

When implementing the technology of obtaining functional coatings, we considered two types of coatings that

work perfectly under different conditions: 1) Antifriction gradient coatings based on metal compositions. As the basis of the metal composition, powdered babbit B83 with a dispersity of 5–45 μm, which has enhanced antifriction properties and high bearing capacity, was used. To increase the tribotechnical properties at higher operating speeds (more than 50 m / s), as well as the efficiency of surface grinding, the powder composition was additionally doped with molybdenum disulfide MoS2.

2) Wear-resistant functional coatings of hammer crushers, operated under conditions of intensive dynamic and abrasive impact. To obtain these coatings, a powder composition of the PG-CP4 brand (GOST 21448-75) with a dispersity of 20-45 μm was used, designed for surfacing parts that are subject to intense wear at temperatures up to 600 C and experiencing impact loads.

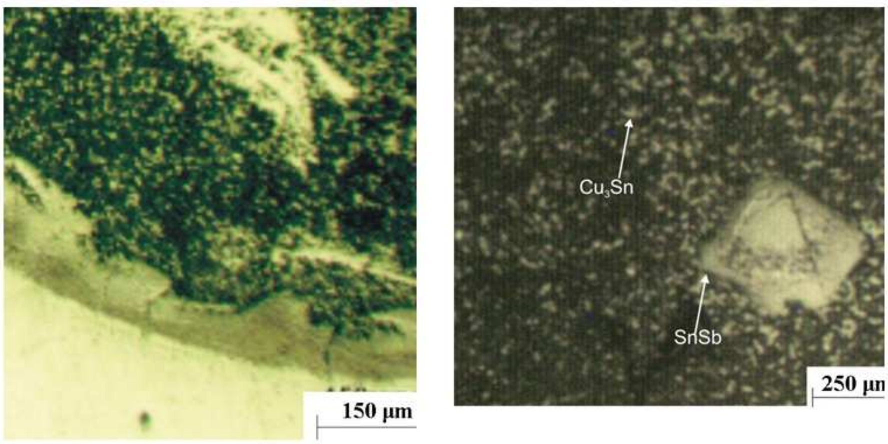
The powder composition was preliminarily subjected to intensive mechanactivation in an AGO-2C ball mill.

Laser radiation with a wavelength of $\lambda = 1.06$ μm, generated by the Bulat solid-state laser generator, was used as an energy source. When the processing speed of the powder composition is 25 mm / s. The treatment process was carried out in a protective atmosphere of argon.

In the formation of functional coatings, special attention was paid to the state of the surface, in particular, to the absence of roughness, pores and cavities. In addition, we analyzed the state of the quality of adhesion of the coating to the surface of the substrate for the absence of delamination from the substrate, the presence of penetration and various segregations. The resulting functional coatings have a surface structure without any visible defects and irregularities. The thickness of the coating, depending on the powder layer is in the range of 85-100 μm.

Anti-friction coatings have a dark color, with a slight caricature. The surface is felt "oily" and layered.

Transverse microsections were prepared for more effective analysis of anti-friction coatings. Microscopic examinations were performed on a Neophot 32 optical microscope. During the analysis, the state of the adhesion zone was monitored for exfoliation and phase nomenclature in the structure.



a) b)

Figure 3: Microstructure of Antifriction Coatings

RESULTS AND DISCUSSIONS

The study of microstructures showed the presence of a soft coating matrix (α - solid solution), solid inclusions

consisting of Sn-Sb intermetallic compounds - β-phase and needle inclusions of γ-phase – Cu_3Sn. As planned, the dispersion of the above mentioned inclusions is significantly greater than that of traditional babbit coatings, which is explained by higher crystallization rates, especially for the γ-phase (Figure 3).

The fusion zone with the substrate is characterized by a pronounced light shade, which indicates the presence of additional phases. The fusion zone does not have pores or lack of penetration, which is a consequence of the optimal processing conditions with the achievement of the necessary strength of the joint. Studies on the determination of adhesion strength in this work have not been carried out, but the impact on the coating did not lead to their detachment from the substrate.

In order to determine the uniform distribution of phases in the bulk of the coating, X-ray structural studies were performed (Figure 4).

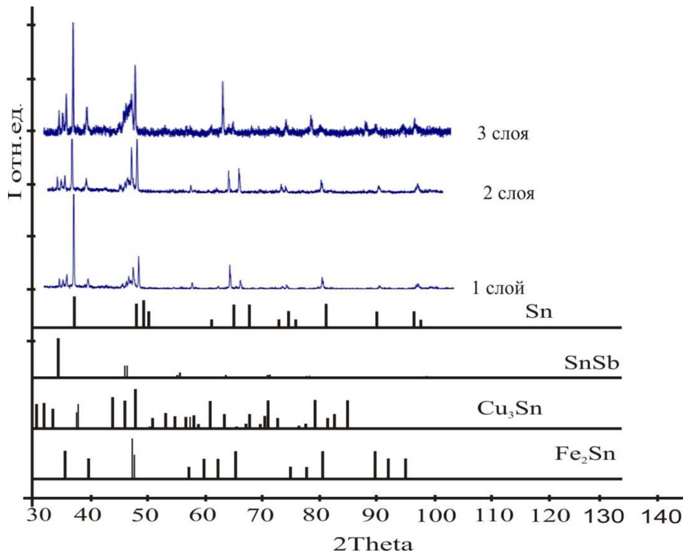


Figure 4: Diffraction Patterns of Coatings, with Increasing Thickness of the Antifriction Coating

These studies were performed on a DRON - 6 diffractometer, in CoKa - radiation with a wavelength of 1.7902 A^0; step angle of 0.05. According to the experiment, the formation of “standard” above intermetallic compounds as well as Fe_2Sn compounds was revealed. The formation of this compound mainly occurs in the underlying layers close to the substrate, which characterizes the processes of mixing the volumes of the metals of the substrate and the applied composite during laser processing. The presence of this phase in the microstructural analysis does not manifest itself, which characterizes its crystalline structure. Since intermetallic compounds have relatively high strength, this ensures high adhesion strength of the applied coating to the substrate. To determine the quantitative composition of the phases by thickness, an x-ray structural analysis was performed, dividing the coating into three conditional layers. The main data of the quantitative analysis are presented in table 1.

Table 1: Phase and Quantitative Composition of the Coating

No	Phase	The Amount of Phase in Layer 1,%	The Amount of Phase in Layer 2,%	The Amount of Phase in Layer 3,%
1	Sn	6,2891	19,7383	0,2473
2	SnSb	44,4778	6,0433	14,1435
3	Cu_3Sn	43,9101	68,2355	84,9430
4	Fe_2Sn	5,3230	5,9829	0,6663

Analyzing the phase composition, it was determined that the phase composition is not homogeneous in thickness, which indicates the presence of gradient mechanical properties. With an increase in the layer thickness, the amount of the Sn phase approached zero, and the amount of the Cu_3Sn intermetallic phase increased significantly. The increase in the concentration of this intermetallic compound occurs due to the increase in laser processing time. The decrease in the Fe_2Sn phase to the surface layer is associated with an increase in the thickness of the applied coating and the absence of iron in the surface layers. Thus, the features of phase transformations during laser processing led to a quantitative change in the composition of phases in thickness. Gradient properties are determined by a softer zone in the area of adhesion with the substrate, characterized by the presence of α-solid solution and β-phase (SnSb), and the surface layers interacting with other surfaces are harder due to an increase in the γ-phase (Cu_3Sn) hardness. This characteristic of the coating fully satisfies the requirements for surfaces operating at high specific loads.

To analyze the performance of the investigated coatings, comparative wear tests were performed under dry friction using the above procedure. A coating of material MU S was tested for comparative analysis (Figure 4). The research results are in line with expectations, in particular, the projected coating is not inferior in its characteristics to the compared material (Goldfarb (2015, Ipatov (2015)). At the initial moment of research, the coatings are subjected to burn-in, which is characterized by intense wear, with high friction moments. However, the test coating is burned in much faster and goes into normal operation, which is explained by the presence of a softer coating structure. The moment of friction during the run-in period for a coating based on MU S is significantly lower, which is explained by the operation of a thin infiltrated coating based on Teflon.

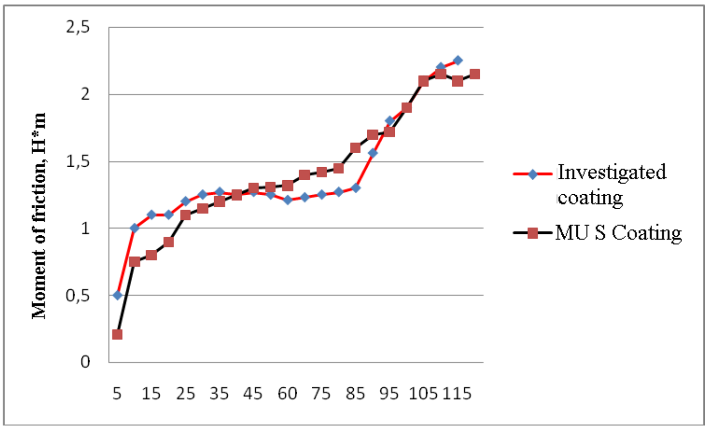


Figure 5: Intensity of Friction Torque Change during Comparative Wear Tests Under Dry Friction Conditions Depending on Test Time

In normal operation, the friction torque of the test coating is more constant and stable. An increase in the friction moment occurs only when the coating is in operation for 90 minutes, followed by an abrupt increase in the friction moment and the destruction of the coating. The explanation may be a feature of the structure of the coating, the gradient of the mechanical properties makes it equally good to withstand high contact loads, as well as high-speed modes, while ensuring high anti-friction properties. To determine the bearing characteristics of the coating, an analysis was made of the magnitude of the frictional moment depending on the applied load, while the exposure time of one load was limited to 5 minutes (Figure 5).

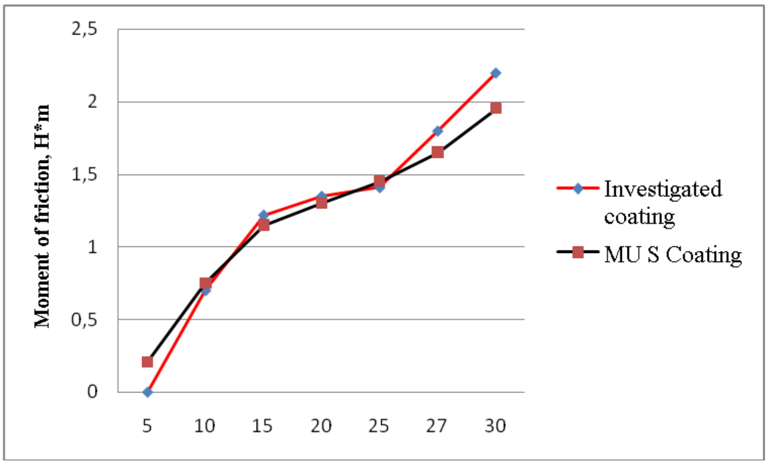


Figure 6: Intensity of Friction Torque change during Comparative Tests Depending on the Applied Load

The bearing capacity of the coating under dry friction conditions is characterized by a smoother variation of the frictional moment with increasing contact load. With an increase in the load of more than 25 MPa, an increase in the frictional moment is observed in the coating under investigation without signs of coating microfracture. When the load increases above 30 MPa, the coating under study shows abrupt changes in friction torque with traces of coating destruction. In the compared coating (from optical analysis of the friction surface), the surface microseeding occurs at the moment of wear of the thin surface layer of Teflon, which corresponds to a load of 23 MPa. With a further increase in the contact load of the coating, friction torque instability is observed with a significant increase in it. The destruction of the coating occurs at a contact load of 37 MPa, which is 23% higher than the indicator of the analyzed coating. Thus, comparative tests showed that the synthesized anti-friction functional coatings showed their high efficiency under dry friction conditions and have great practical potential.

Wear-resistant functional coatings based on the powder composition PG-CP4 were implemented on the surface of hammer crushers made of medium carbon steel Steel 65G.

In order to analyze the performance of the formed functional coatings, production tests were carried out on the basis of an enterprise for the processing of rocks, using a hammer mill crusher (Figure 6).

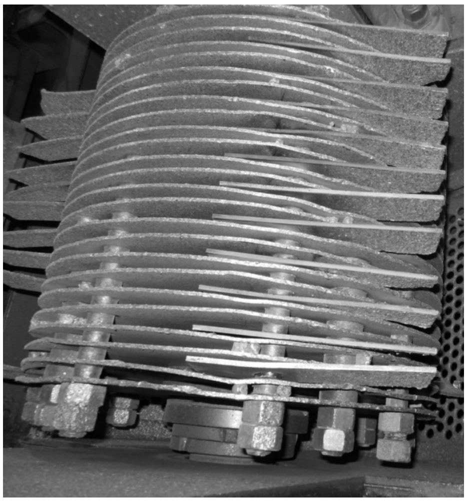


Figure 7: Drum Crushers with Wear-Resistant Hammers after Testing

In the process of testing, calcium was used as a material for crushing. Complete with modified hammers used standard hammers made of steel 65G and manufactured by the industry. During operational studies, the amount of time in tons of the processed material was monitored, as well as the time to failure (breakage of the crusher hammer). Based on the studies, the wear resistance of the studied and standard hammers was determined (Figure 7).

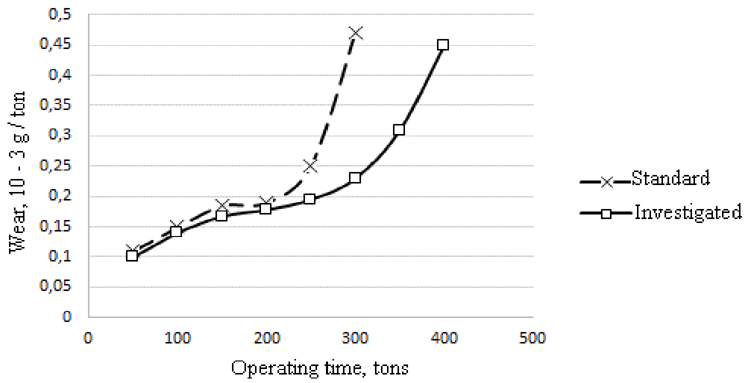


Figure 8: Comparative Amount of Wear, Standard and Test Samples

The amount of wear of the test sample with a functional wear-resistant coating at up to 200 tons of rock is slightly lower than the standard sample. This behavior is easily explained by the workability of the contacting surfaces. During the production of more than 200 tons of rock, the amount of wear of the standard sample increases and mainly turns into intensive dispersion with fatigue destruction of the surface, which indicates significant fatigue loads. On the contrary, the sample under study is more resistant to fatigue stress, which indicates a high resistance to fatigue failure. In this case, fatigue failure is not observed. Resistance to fatigue failure clearly demonstrates the presence of a soft matrix in the coating, mainly on a nickel base, and solid inclusions of carbides withstand intense wear.

To explain in more detail, we performed further laboratory studies of functional coatings. For this purpose, microsections of the samples were made in cross section. The etching of microsections during metallographic analysis revealed only a white zone, which indicates an intense thermal effect and the formation of metastable structures. In this regard, the main goal of metallographic analysis was to determine the porosity of the coating (Figure 8). The analysis of three microsections characterized the porosity of the coating within 25... 30%. At the same time, the porosity varies significantly from the substrate to the coating surface: in the adhesion zone, the porosity is almost zero, which indicates a high degree of mixing of the material of the powder composition and the thin surface layer. On the surface of the coating, the porosity reaches 50%, which is explained by the high level of gas formation in the melting zone, as well as the oxidation of the components of the powder composition.

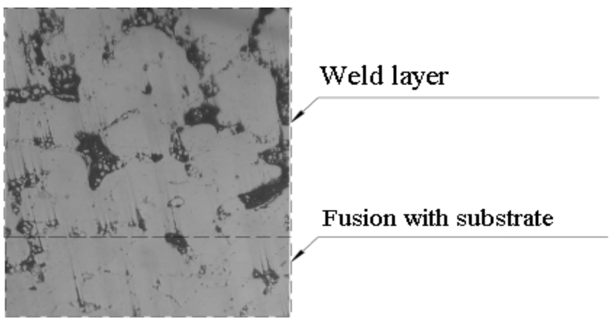
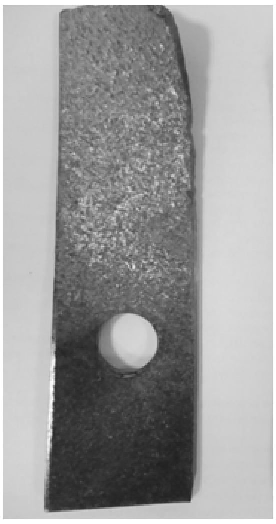


Figure 8: Microstructure of the Wear-Resistant Weld Layer

We prepared a microsection without chemical etching to determine the microhardness. Microhardness was determined by the thickness of the coating from the substrate to the surface, at certain intervals (Figure 6). For punctures, Microhardness of the analyzed coating was chosen from 430... 450HV (corresponding to 40... 45HRC), with a base hardness of 235... 240 HB.

According to the results of operational research, it was revealed that a batch of 4 modified hammers with weld wear-resistant coatings after grinding 350 tons of calcium did not wear out. Two hammers collapsed due to deformation and subsequent fracture over the cross section of the mounting hole. The mounting hole of the standard hammer also underwent a slight deformation, however, no cranks were recorded.



a

b

Figure 8: The State of the Mounting Holes of the Standard (a) and Modified (b) Hammers

In the presented figure of the sample under study, the destruction of the working surface of the hammer under the effect of shock loads is well seen: standard hammers are subject to more intensive wear and destruction, because they have a sufficiently low plasticity, which causes intercrystalline destruction of the hammer surface even with small impacts (Figure 8a). The modified hammers were deformed and collapsed to a lesser extent (Figure 8b). The explanation is the high hardness of the deposited layer, which is characterized by minimal deformation, and the soft base of the hammer provides high resistance to shock loads. Thus, the presented results demonstrate the fact that during high-speed synthesis of functional coatings from powder materials, a structure with a gradient structure is also formed. The presented research results indicate high durability of functional coatings, which is operated under conditions of intensive abrasive and impact. Durability of hammers with a deposited coating exceeds the standard knife by 27%.

Studies on high-speed laser synthesis of functional coatings from ultrafine powder materials for various purposes have demonstrated the veracity of expectations for obtaining gradient functional coatings in one treatment. The research results exceed the parameters of the physicomechanical properties of standard or similar surfaces, in particular, the wear resistance of functional anti-friction coatings under dry friction conditions is 15-20% higher than those of standard coatings, and the resistance of coatings to maximum contact loads exceeds by 50% or more.

CONCLUSIONS

Functional wear-resistant coatings implemented on the surface of hammers of hammer crushers have excellent abrasive wear resistance, as well as high damping properties and the ability to withstand significant impact loads. The adhesion of the obtained coatings corresponds to the strength of the substrate and does not undergo peeling during operation.

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